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A. G. Illarionov, S. I. Stepanov, and S. L. Demakov

# Fracture Surface Analysis of a Quenched (α+β)-Metastable Titanium Alloy

A. G. Illarionov[a)], S. I. Stepanov[b)] and S. L. Demakov[c)]

*Ural Federal University named after the First President of Russia B. N. Yeltsin, 19 Mira St., Ekaterinburg, Russia, 620002*

[a)]illarionovag@mail.ru
[b)]Corresponding author: s.i.stepanov@urfu.ru
[c)]demakof@mail.ru

**Abstract.** Fracture surface analysis is conducted by means of SEM for VT16 titanium alloy specimens solution-treated at temperatures ranging from 700 to 875 °C, water-quenched and subjected to tensile testing. A cup and cone shape failure and dimple microstructure of the fracture surface indicates the ductile behavior of the alloy. Dimple dimensions correlated with the β-grain size of the alloy in quenched condition. The fracture area (namely, the size; the cup and cone shape) depends on the volume fraction of the primary α-phase in the quenched sample. However, the fracture surface changes considerably when the strain-induced β-α″-transformation takes place during tensile testing, resulting in the increase of alloy ductility.

## INTRODUCTION

VT16 (Ti-3Al-5Mo-5V) is a two-phase (α+β)-metastable alloy hardenable by heat treatment including solution treatment, water quenching and ageing [1]. The alloy is capable of cold working after quenching [2, 3]. However, the power of cold working depends on the phase and structural conditions, which mainly determine the ductility of the alloy. The structure, phase composition and mechanical properties were discussed in [4, 5] depending on the quenching from a wide range of temperatures. Nevertheless, the relation between the fracture during tensile testing and the phase composition, as well as the level of alloy ductility after quenching, has yet to be studied. The present study is devoted to this aspect.

## MATERIAL AND METHODS

Hot-rolled and annealed rods, 11 mm in diameter, made of VT16 (Ti-3.33Al-5.18Mo-4.57V, wt%) were produced by industrial technology at the VSMPO-AVISMA corporation. The rods were solution-treated at a temperature ranging from 700 to 875 °C (the heating step was 25 °C) for 1 hour and water-quenched. The quenched rods were cut into dog-bone shape specimens for tensile testing on an FP100/1 testing machine in accordance with ISO 6892-1. The fracture surface of the tested specimens was studied using an FEI Quanta 3D scanning electron microscope.

## RESULTS AND DISCUSSION

The structure of the fracture surface of the VT16 alloy quenched from different temperatures and tensile-tested is presented in Fig. 1. Fractographic examination demonstrates that the fracture surfaces are straight, with bevels, and characterized by cup and cone shapes after all quenching temperatures [6]. A fiber structure is typical of the "cup" surface according to the comparative analysis with the data of the fracture handbook [7]. In addition, the radial zone, which generally indicates a brittle failure, is absent between the "cup" and the "cone" (shear zone). A dimple configuration of the surface microstructure is observed for all the quenched samples which argues for ductile failure as well [6,7].

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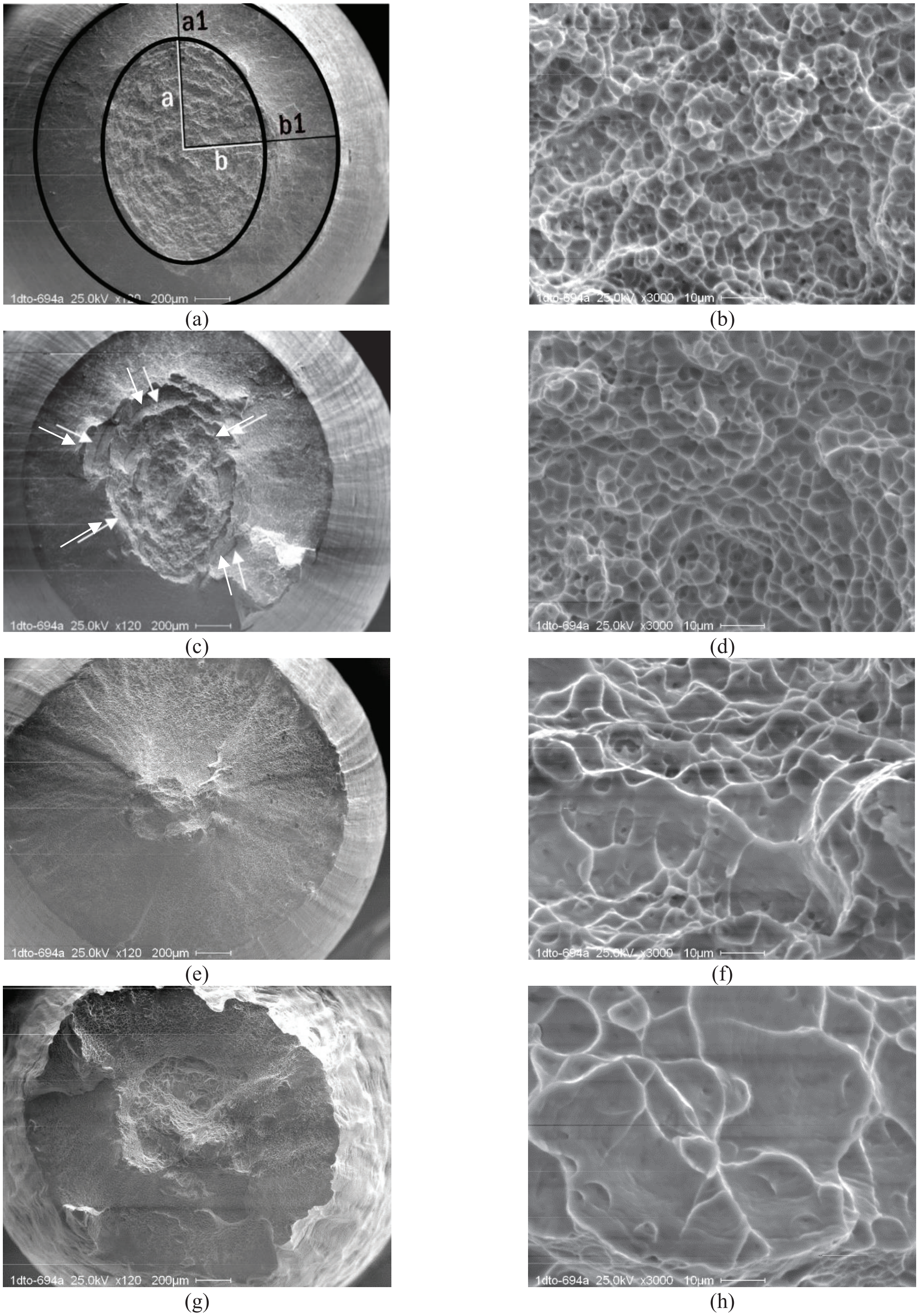


**FIGURE 1.** The structure of the fracture surface of VT16 samples, solution-treated at 725 °C (a, b), 775 °C (c, d), 850 °C (e, f) and 875 °C (g, h) for 1 hour and quenched.

Such fracture is characteristic of titanium alloys. According to the data reported in [8], failure during tensile testing includes the following steps: 1) macroplastic deformation accompanied by necking; 2) origination and development of micropores in the central region of the specimen; 3) interaction of the microdefects and formation of the cup surface normal to the stress axis; 4) slow crack propagation from the cup edge along the conical surface; 5) fast propagation of the crack developing by the shear mechanism. The stress field in the tensile specimen represents the superimposition of uniaxial and hydrostatic tensile stresses [9]. The latter turns into zero in the periphery region of the circular cross-section and reaches its maximal value in the center. Since the normal stress is maximal along the axis, the fracture of the bone-shape specimen with a reduced cylindrical section starts from the origination and development of pores in the central, axial, region.

A void develops in the center of the specimen as a result of pore coalescence. This void is bounded by the dimple surface, which is perpendicular to the axis of the normal stress in the microscale. The void grows radially by means of continuous failure or coalescence of pores originating in front of the propagation direction. Further crack propagation shits the crack tip to the region where the effect of hydrostatic stresses decreases and the shear stresses play a considerable role. Therefore, the crack changes its orientation and twists. This is accompanied by a transition from the cup surface to the cone one.

The relationship among the fracture zone features, the structure characteristics, the phase composition and the ductility of the alloy under study has been stated (Fig. 1, Table 1).

**TABLE 1.** The phase composition, elongation and geometric parameters of the fracture surface of the solution-treated and quenched VT16 alloy

| $T_q$, °C | 700 | 725 | 750 | 775 | 800 | 825 | 850 | 875 |
|---|---|---|---|---|---|---|---|---|
| Phase [4] | α+β | α+β | α+β | β+α+α″ | α″+α+ β | α″+α+ β | α″+α | α″+(α) |
| δ, % [5] | 15 | 18 | 17 | 18 | 20 | 20 | 22 | 23 |
| a, μm | 500 | 500 | 500 | 400-450 | 225 | 175 | 150 | 300 |
| b, μm | 700 | 650 | 625 | 585 | 250-300 | 250-275 | 200-275 | 300 |
| a1, μm | 875 | 885 | 950 | 900 | 950 | 945 | 950 | 875 |
| b1, μm | 1000 | 1000 | 1000 | 1000 | 1050 | 1000 | 1000 | 900 |
| a1-a | 375 | 385 | 450 | 475 | 725 | 825 | 800 | 575 |
| b1-b | 300 | 350 | 375 | 415 | 775 | 725 | 762 | 600 |
| b/a | 1.4 | 1.3 | 1.25 | 1.38 | 1.22 | 1.5 | 1.58 | 1 |
| b1/a1 | 1.14 | 1.13 | 1.07 | 1.11 | 1.105 | 1.06 | 1.05 | 1.03 |

Thus, the average dimple diameter of the quenched specimens correlates with the average β-grain size, which is determined by the primary α-phase fraction having a size of about 3 μm for the quenching temperature ranging between 700 and 775 °C, 5 μm for $T_q$ = 800 °C, 10 to 13 μm for $T_q$ = 825-850 °C and 70 μm for $T_q$ = 875 °C, according to the data reported in [5]. Thus, we conclude that fracture is initiated at the interphase α/β-boundary, and then it propagates into the β-grain body, this being accompanied by the formation of dimples with dimensions comparable to the β-grain size. Another confirmation of this is the presence of α-particles at the bottom of the dimples. Note that the depth of the visually estimated dimples increases along with the β-grain growth. In addition, a typical topography of the tensile specimen surface is observed out of the fracture zone of the specimen of the alloy quenched from 875 °C (Fig. 1g), which is apparently related to the large β-grain size.

The profile of the cup and cone surface is characterized by a well-defined oval shape for the specimens quenched from the temperatures ranging between 700 and 825 °C, which contain a significant fraction of the α-phase, namely, 60% for $T_q$ = 700 °C and 20% for $T_q$ = 825 °C. In addition, in the conical region of the fracture surface, the relationship between the lengths of the major and minor axes (a, b, a1, b1) of the oval decreases, the volume fraction of the α-phase decreases, too, with the increase of the solution treatment temperature (Fig. 1, Table 1). This effect is related to the anisotropy of the failure process due to the presence of the α-phase, whose HCP lattice is more anisotropic than the BCC lattice of the β-phase.

The elongation of the specimen during tensile testing correlates well with the dimensional ratio of the central fiber region of the cup and the periphery region of the cone (Fig. 1, Table 1). For the majority of the specimens, the higher values of the elongation are observed as the width of the cone zone increases and the size of the cup zone decreases (Fig. 1), and this is characteristic of ductile materials [7].

On the fracture surface of the specimens quenched from 750 and 775 °C, hollows and protrusions develop at the border between the cup and the cone (Fig. 1 c, marked with arrows). The structure of the fracture surface in these regions is similar to the shear zone. However, the crack propagates changing its direction in contrast to the shear zone, where the only direction is typical. We suppose that this effect is due to the strain-induced β-α″-transformation during the tensile test and the appearance of α″-martensite in the structure of the alloy, according to the data found in [5]. As a result, the yield strength decreases substantially and the strain hardening value increases. Thus, the unstable failure process may occur due to significant local hardening when passing to the shear zone.

Therefore, the fracture surface of the VT16 metastable (α+β)-titanium alloy, solution-treated at temperatures ranging between 700 and 875 °C and water-quenched, has a typical dimple microstructure intrinsic to ductile materials. The size of the dimples correlate well with the size of β-grains obtained during solution treatment. The structural features of the fracture zone (dimensions and shape of the cup/cone zones) are attributed to the phase composition changes, namely, the volume fraction of the primary α-phase and the formation of α″-martensite with regard to the strain-induced β-α″-transformation occurs during tensile testing. Ductility is estimated during tensile testing of the quenched alloy, and it has been determined by the above-mentioned fracture features.

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